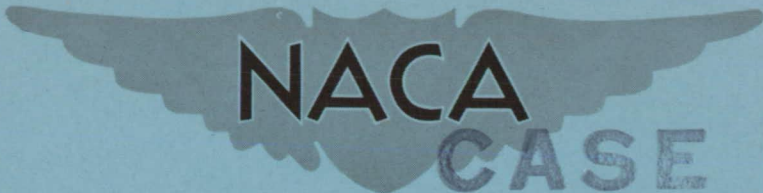


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RESEARCH MEMORANDUM

THEORETICAL PERFORMANCE OF LIQUID AMMONIA, HYDRAZINE,
AND MIXTURE OF LIQUID AMMONIA AND HYDRAZINE AS FUELS
WITH LIQUID OXYGEN BIFLUORIDE AS OXIDANT
FOR ROCKET ENGINES

III - LIQUID AMMONIA

By Vearl N. Huff and Sanford Gordon

Lewis Flight Propulsion Laboratory
Cleveland, Ohio

CLASSIFIED DOCUMENT

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RESEARCH MEMORANDUM

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FOR ROCKET ENGINES

III - LIQUID AMMONIA

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SUMMARY

Theoretical values of performance parameters for liquid ammonia with liquid oxygen bifluoride were calculated on the assumption of equilibrium composition during the expansion process for a wide range of fuel-oxidant and expansion ratios. Parameters included were specific impulse, combustion-chamber temperature, nozzle-exit temperature, equilibrium composition, mean molecular weight, characteristic velocity, coefficient of thrust, and ratio of nozzle-exit area to throat area.

The maximum value of specific impulse was 291.6 pound-seconds per pound for a chamber pressure of 300 pounds per square inch absolute (20.41 atm) and an exit pressure of 1 atmosphere.

INTRODUCTION

Liquid ammonia has been of interest for a number of years as a possible rocket fuel because of its high theoretical specific impulse with several oxidants. Extensive data on ammonia exist in the literature.

Oxygen bifluoride is of interest as a rocket oxidant because its performance is better than that of oxygen, its handling and material problems may be simpler than those of fluorine, and its density is greater than either oxygen or fluorine. Additional information concerning oxygen bifluoride may be found in reference 1.

The performance of hydrazine and of a mixture of ammonia and hydrazine as a fuel with oxygen bifluoride as an oxidant was reported in parts I and II of this series (references 2 and 3). A limited amount of performance data of liquid ammonia with liquid oxygen bifluoride has been

reported in the literature. Additional calculations for this propellant were made at the NACA Lewis laboratory to determine a larger number of performance parameters over a wider range of conditions than previously published.

Data were calculated on the basis of equilibrium composition during expansion and cover a wide range of fuel-oxidant and expansion ratios. The performance parameters included are specific impulse, combustion-chamber temperature, nozzle-exit temperature, equilibrium composition, mean molecular weight, characteristic velocity, coefficient of thrust, and ratio of nozzle-exit area to throat area.

SYMBOLS

The following symbols are used in this report:

A	number of equivalent formulas (a function of pressure and molecular weight; see reference 5)
A_e/A_t	ratio of nozzle-exit area to throat area
a	local velocity of sound, ft/sec
C_F	coefficient of thrust
c_p/c_v	ratio of specific heats
c^*	characteristic velocity, ft/sec
D_A	$\left(\frac{\partial \log A}{\partial \log T}\right)_s$
D_i	$\left(\frac{\partial \log p_i}{\partial \log T}\right)_s$
$f_1, f_2, \dots, f_5$	functions
h	enthalpy, including both sensible and chemical energy per unit weight, cal/g
I	specific impulse, lb-sec/lb
M	mean molecular weight, g/mole
n	number of atoms

P	pressure
P_i	partial pressure of a product of combustion
R	gas constant (consistent units)
r	equivalence ratio, ratio of number of hydrogen atoms to sum of number of fluorine atoms plus two times number of oxygen atoms in propellant $\left(\frac{n_H}{n_F + 2n_O} \right)$
T	temperature, °K
r_s	$\left(\frac{\partial \log P}{\partial \log \rho} \right)_s$
ρ	density
Subscripts:	
c	combustion chamber
e	nozzle exit
max	maximum
o	conditions at 0° K, assuming recombination is complete
s	constant entropy

METHOD OF CALCULATION

Calculations were made with an IBM Card Programmed Electronic Calculator as described in reference 2. The set of assumptions, products of combustion, and thermodynamic data used for the calculations are the same as those of reference 2. The dissociation energy of fluorine F_2 was taken to be 35.6 kilocalories per mole (reference 4).

Procedure for combustion conditions. - The values of temperature, entropy, equilibrium composition, and mean molecular weight of the products of combustion corresponding to an adiabatic combustion process were obtained for eight equivalence ratios as described in reference 2.

Procedure for exit conditions. - Equilibrium composition, mean molecular weight, pressure, derivative of the logarithm of pressure with

respect to the logarithm of density at constant entropy γ_s , and enthalpy of the products of combustion were computed for each equivalence ratio by assuming isentropic expansion for six assigned exit temperatures covering the exit pressure range from the nozzle-throat pressure to about 0.02 atmosphere. The derivative γ_s is equal to the ratio of specific heats c_p/c_v only when the molecular weight is constant (reference 3).

Throat parameters and exit parameters corresponding to altitudes of 0, 20,000, 40,000, 60,000, and 80,000 feet were interpolated by means of cubic equations between each pair of the assigned exit temperatures; the functions and their first derivatives used are described in reference 3.

The errors due to interpolation were checked for several cases. The values presented for all performance parameters appear to be correctly interpolated to one or two units in the last place tabulated.

THEORETICAL PERFORMANCE

The calculated values of the various performance parameters for a combustion pressure of 300 pounds per square inch absolute and at exit pressures corresponding to altitudes of 0, 20,000, 40,000, 60,000, and 80,000 feet are given in table I for eight equivalence ratios. The values of pressure corresponding to the assigned altitudes were taken from references 6 and 7. Equilibrium composition and γ_s in the combustion chamber and at assigned exit temperatures are given in table II.

The parameters are plotted in figures 1 to 7. Curves of specific impulse for the five altitudes are shown in figure 1 plotted against weight-percent fuel. The maximum value of specific impulse for the sea-level curve is 291.6 pound-seconds per pound at 32.0 percent fuel by weight.

The maximum values of specific impulse and the values of weight-percent fuel at which they occur are shown plotted in figure 2 as functions of altitude. The maximum specific impulse increases 31.8 percent for a change in altitude from sea level to 80,000 feet.

Curves of combustion-chamber temperature and nozzle-exit temperature for the five altitudes are presented in figure 3 as functions of weight-percent fuel. The maximum combustion temperature occurs at the extreme oxidant-rich end of the curve, being 3837° K at 17.4 percent fuel by weight. The maximums of the exit-temperature curves occur near the stoichiometric mixture.

Characteristic velocity and coefficient of thrust are plotted in figure 4 and ratios of the area at the nozzle exit to area at the throat are shown in figure 5 as functions of weight-percent fuel.

Curves of mean molecular weight in the combustion chamber and in the nozzle exit are shown plotted against weight-percent fuel in figure 6.

Values of the parameters c^* , C_F , and A_e/A_t for a constant expansion ratio are only slight functions of chamber pressure and may be used at other pressures with small error.

The data of references 2 and 3 may be used with the data of this report to show the effect of the amount of ammonia in an ammonia-hydrazine mixture on the performance parameters. Curves are presented in figure 7 for I , c^* , and A_e/A_t for an expansion ratio of 20.41 as a function of weight percentage of ammonia in the fuel. One set of curves is for the stoichiometric equivalence ratio and the other set is for the equivalence ratio corresponding to maximum I .

Similar curves may be plotted for any equivalence ratio and expansion ratio covered by the data in this series of reports and used to obtain the performance of any mixture of ammonia and hydrazine with oxygen bifluoride. However, these curves are very nearly linear, and only small errors in performance result from linear interpolation of the tabulated data.

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TABLE I - CALCULATED PERFORMANCE OF AMMONIA WITH OXYGEN BIFLUORIDE
[Combustion-chamber pressure, 300 lb/sq in. absolute]



Equiv- alence ratio r	Propellant		Combustion chamber		Character- istic velocity c* (ft/sec)	Nozzle exit					Coeffi- cient of thrust C _p	Specific impulse I _s (lb-sec/lb)
	Weight- percent fuel	density (g/cc)	Temper- ature T _c (°K)	Mean molec- ular weight M _c		Altitude (ft)	Pressure P (atm)	Temper- ature T _e (°K)	Mean molecular weight M _e	Ratio of nozzle- exit area to throat area A _e /A _t		
0.50	17.37	1.384	3837	21.33	6275	0	1	2706	22.76	3.874	1.424	277.7
						20,000	0.4594	2400	22.95	6.785	1.557	303.6
						40,000	.1852	2013	23.05	13.03	1.679	327.5
						60,000	.07125	1617	23.07	25.68	1.778	346.7
						80,000	.02780	1279	23.07	50.00	1.852	361.1
0.75	23.98	1.279	3792	19.92	6453	0	1	2722	21.43	3.909	1.426	285.9
						20,000	0.4594	2448	21.67	6.916	1.560	312.9
						40,000	.1852	2098	21.81	13.51	1.686	338.1
						60,000	.07125	1720	21.85	27.08	1.789	358.8
						80,000	.02780	1383	21.86	53.47	1.867	374.6
1.00	29.60	1.200	3690	18.82	6557	0	1	2896	20.31	3.952	1.428	291.0
						20,000	0.4594	2454	20.58	7.054	1.564	318.7
						40,000	.1852	2154	20.79	14.03	1.693	345.1
						60,000	.07125	1813	20.90	28.72	1.802	367.2
						80,000	.02780	1484	20.92	57.51	1.885	384.3
1.25	34.46	1.140	3551	17.88	6589	0	1	2415	18.93	3.778	1.420	290.8
						20,000	0.4594	2062	19.00	6.485	1.548	317.1
						40,000	.1852	1714	19.01	12.30	1.664	340.9
						60,000	.07125	1377	19.01	24.34	1.759	360.0
						80,000	.02780	1098	19.01	47.83	1.828	374.3
1.50	38.68	1.093	3358	17.04	6524	0	1	2045	17.60	3.546	1.406	285.1
						20,000	0.4594	1724	17.61	5.997	1.525	309.3
						40,000	.1852	1398	17.61	11.27	1.632	331.0
						60,000	.07125	1109	17.61	22.09	1.717	348.2
						80,000	.02780	874	17.61	43.01	1.781	361.1
1.75	42.39	1.054	3123	16.27	6383	0	1	1752	16.54	3.400	1.397	277.1
						20,000	0.4594	1463	16.54	5.714	1.510	299.7
						40,000	.1852	1174	16.54	10.66	1.612	319.8
						60,000	.07125	922	16.54	20.74	1.692	335.7
						80,000	.02780	721	16.54	40.11	1.752	347.5
2.00	45.68	1.022	2872	15.58	6201	0	1	1523	15.70	3.312	1.392	268.2
						20,000	0.4594	1263	15.70	5.537	1.502	289.5
						40,000	.1852	1005	15.70	10.27	1.600	308.5
						60,000	.07125	784	15.70	19.85	1.677	323.3
						80,000	.02780	609	15.70	38.2	1.734	334.3
2.50	51.25	0.972	2389	14.43	5804	0	1	1186	14.45	3.209	1.387	250.3
						20,000	0.4594	973	14.45	5.318	1.494	269.6
						40,000	.1852	765	14.45	9.768	1.588	286.5
						60,000	.07125	591	14.45	18.7	1.661	299.7
						80,000	.02780	454	14.45	35.7	1.716	309.6

^aBased on OF₂ density of 1.77 at -195.8° C.

TABLE II - EQUILIBRIUM COMPOSITION AND γ_s IN COMBUSTION CHAMBER AND FOLLOWING AN ISENTROPIC EXPANSION TO ASSIGNED EXIT TEMPERATURES FOR AMMONIA WITH OXYGEN BIFLUORIDE



Temperature T (°K)	Pressure P (atm)	γ_s $\left(\frac{\partial \log P}{\partial \log p_s}\right)$	Equilibrium composition (mole fraction)										
			HF	H ₂	H ₂ O	OH	O ₂	NO	N ₂	F	H	O	N
			$r = 0.50$ (17.37 percent fuel by weight)										
3837	20.41	1.1551	0.58540	0.00323	0.01030	0.02543	0.09459	0.02518	0.09502	0.06735	0.01486	0.07628	0.00236
3700	14.52	1.1538	.59905	.00261	.00984	.02272	.10169	.02378	.09699	.05972	.01211	.06966	.00184
3200	3.846	1.1560	.64631	.00093	.00747	.01264	.13019	.01770	.10421	.03378	.00434	.04185	.00057
2700	0.9830	1.1819	.68277	.00016	.00424	.00443	.15680	.01070	.11073	.01396	.00073	.01540	.00009
2300	.3612	1.2328	.69871	.00002	.00182	.00105	.16979	.00562	.11444	.00480	.00006	.00368	.00001
1800	.1121	1.3018	.70511	-----	.00028	.00005	.17541	.00155	.11684	.00060	-----	.00017	-----
1200	.02167	1.3482	.70588	-----	-----	-----	.17643	.00008	.11761	-----	-----	-----	-----
$r = 0.75$ (23.98 percent fuel by weight)													
3792	20.41	1.1560	0.54299	0.02995	0.07230	0.05237	0.04443	0.01946	0.12929	0.01789	0.04148	0.04746	0.00239
3600	12.48	1.1536	.55537	.02673	.08107	.04836	.04815	.01765	.13256	.01347	.03393	.04104	.00166
3200	4.100	1.1520	.57921	.01876	.10276	.03741	.05629	.01346	.13938	.00651	.01893	.02665	.00064
2800	1.257	1.1619	.59847	.00991	.12610	.02363	.08428	.00907	.14561	.00244	.00724	.01308	.00016
2400	0.4035	1.1977	.61026	.00309	.14399	.01049	.07098	.00507	.15017	.00061	.00139	.00392	.00002
1900	.1129	1.2681	.61491	.00022	.15268	.00169	.07562	.00160	.15294	.00004	.00003	.00027	-----
1400	.02926	1.3126	.61537	-----	.15381	.00006	.07680	.00021	.15374	-----	-----	-----	-----
$r = 1.00$ (29.60 percent fuel by weight)													
3690	20.41	1.1525	0.48320	0.07007	0.12950	0.04739	0.01659	0.01211	0.15659	0.00759	0.05184	0.02320	0.00190
3500	12.17	1.1494	.49268	.06471	.14452	.04237	.01640	.01040	.16022	.00551	.04288	.01900	.00130
3000	2.686	1.1464	.51638	.04587	.19076	.02631	.01380	.00587	.16964	.00187	.02056	.00860	.00034
2700	1.013	1.1531	.52852	.03181	.22014	.01609	.01050	.00348	.17463	.00076	.01004	.00393	.00011
2300	0.2852	1.1839	.53970	.01386	.25233	.00546	.00509	.00122	.17933	.00014	.00213	.00072	.00001
1900	.09056	1.2404	.54437	.00323	.26847	.00086	.00130	.00023	.18135	.00001	.00015	.00004	-----
1400	.02149	1.2964	.54542	.00012	.27259	.00001	.00005	.00001	.18180	-----	-----	-----	-----
$r = 1.25$ (34.46 percent fuel by weight)													
3551	20.41	1.1557	0.43094	0.12334	0.16283	0.03088	0.00441	0.00592	0.17731	0.00322	0.05124	0.00863	0.00126
3400	13.65	1.1552	.43647	.12071	.17454	.02628	.00365	.00475	.18002	.00235	.04380	.00654	.00089
2900	3.436	1.1694	.45197	.11354	.21029	.01087	.00106	.00151	.18770	.00056	.02082	.00148	.00019
2500	1.227	1.2106	.45883	.11304	.22598	.00281	.00012	.00028	.19106	.00009	.00761	.00015	.00003
2100	0.4791	1.2580	.46110	.11470	.23021	.00031	-----	.00002	.19212	.00001	.00152	-----	-----
1600	.1365	1.2933	.46153	.11536	.23076	-----	-----	-----	.19230	-----	.00005	-----	-----
1100	.02798	1.3259	.46154	.11538	.23077	-----	-----	-----	.19231	-----	-----	-----	-----

TABLE II - EQUILIBRIUM COMPOSITION AND γ_s IN COMBUSTION CHAMBER AND FOLLOWING AN ISENTROPIC EXPANSION TO ASSIGNED EXIT TEMPERATURES FOR AMMONIA WITH OXYGEN BIFLUORIDE - Concluded



Temperature T (°K)	Pressure P (atm)	γ_s $\left(\frac{\partial \log P}{\partial \log p}\right)_s$	Equilibrium composition (mole fraction)										
			HF	H ₂	H ₂ O	OH	O ₂	NO	N ₂	F	H	O	N
r = 1.50 (38.68 percent fuel by weight)													
3358	20.41	1.1711	0.38578	0.18738	0.17250	0.01498	0.00079	0.00219	0.19205	0.00116	0.04031	0.00222	0.00064
3200	13.98	1.1762	.38924	.18857	.17994	.01119	.00050	.00150	.19404	.00075	.03251	.00136	.00041
2700	4.337	1.2102	.39677	.19439	.19516	.00279	.00005	.00026	.19828	.00011	.01199	.00013	.00006
2200	1.423	1.2582	.39952	.19886	.19949	.00025	-----	.00001	.19875	.00001	.00210	-----	-----
1700	0.4314	1.2924	.39998	.19994	.19999	-----	-----	-----	.19999	-----	.00010	-----	-----
1200	.09817	1.3231	.40000	.20000	.20000	-----	-----	-----	.20000	-----	-----	-----	-----
800	.01980	1.3545	.40000	.20000	.20000	-----	-----	-----	.20000	-----	-----	-----	-----
r = 1.75 (42.39 percent fuel by weight)													
3123	20.41	1.1953	0.34677	0.25201	0.16666	0.00565	0.00010	0.00064	0.20204	0.00034	0.02513	0.00040	0.00024
2900	12.63	1.2089	.34921	.25599	.17109	.00307	.00004	.00030	.20359	.00015	.01630	.00015	.00010
2400	4.573	1.2494	.35216	.26244	.17563	.00042	-----	.00003	.20542	.00001	.00389	.00001	.00001
1800	1.128	1.2909	.35291	.26460	.17645	.00001	-----	-----	.20586	-----	.00017	-----	-----
1300	0.2806	1.3198	.35294	.26471	.17647	-----	-----	-----	.20588	-----	-----	-----	-----
1000	.09764	1.3416	.35294	.26471	.17647	-----	-----	-----	.20588	-----	-----	-----	-----
700	.02494	1.3649	.35294	.26471	.17647	-----	-----	-----	.20588	-----	-----	-----	-----
r = 2.00 (45.68 percent fuel by weight)													
2872	20.41	1.2222	0.31333	0.30816	0.15471	0.00177	0.00001	0.00015	0.20883	0.00008	0.01282	0.00005	0.00007
2700	14.42	1.2342	.31426	.31074	.15608	.00097	-----	.00007	.20948	.00004	.00831	.00002	.00003
2200	5.127	1.2708	.31555	.31491	.15769	.00008	-----	-----	.21037	-----	.00139	-----	-----
1500	0.9386	1.3104	.31579	.31578	.15789	-----	-----	-----	.21053	-----	.00001	-----	-----
1100	.2639	1.3367	.31579	.31579	.15789	-----	-----	-----	.21053	-----	-----	-----	-----
900	.1206	1.3522	.31579	.31579	.15789	-----	-----	-----	.21053	-----	-----	-----	-----
700	.04663	1.3672	.31579	.31579	.15789	-----	-----	-----	.21053	-----	-----	-----	-----
r = 2.50 (51.25 percent fuel by weight)													
2389	20.41	1.2678	0.26058	0.38990	0.13017	0.00011	-----	0.00001	0.21715	-----	0.00208	-----	-----
2200	13.87	1.2786	.26074	.39066	.13033	.00004	-----	-----	.21728	-----	.00094	-----	-----
1700	4.424	1.3042	.26086	.39127	.13043	-----	-----	-----	.21739	-----	.00004	-----	-----
1300	1.445	1.3271	.26087	.39130	.13043	-----	-----	-----	.21739	-----	-----	-----	-----
900	0.3411	1.3561	.26087	.39130	.13043	-----	-----	-----	.21739	-----	-----	-----	-----
700	.1329	1.3706	.26087	.39130	.13043	-----	-----	-----	.21739	-----	-----	-----	-----

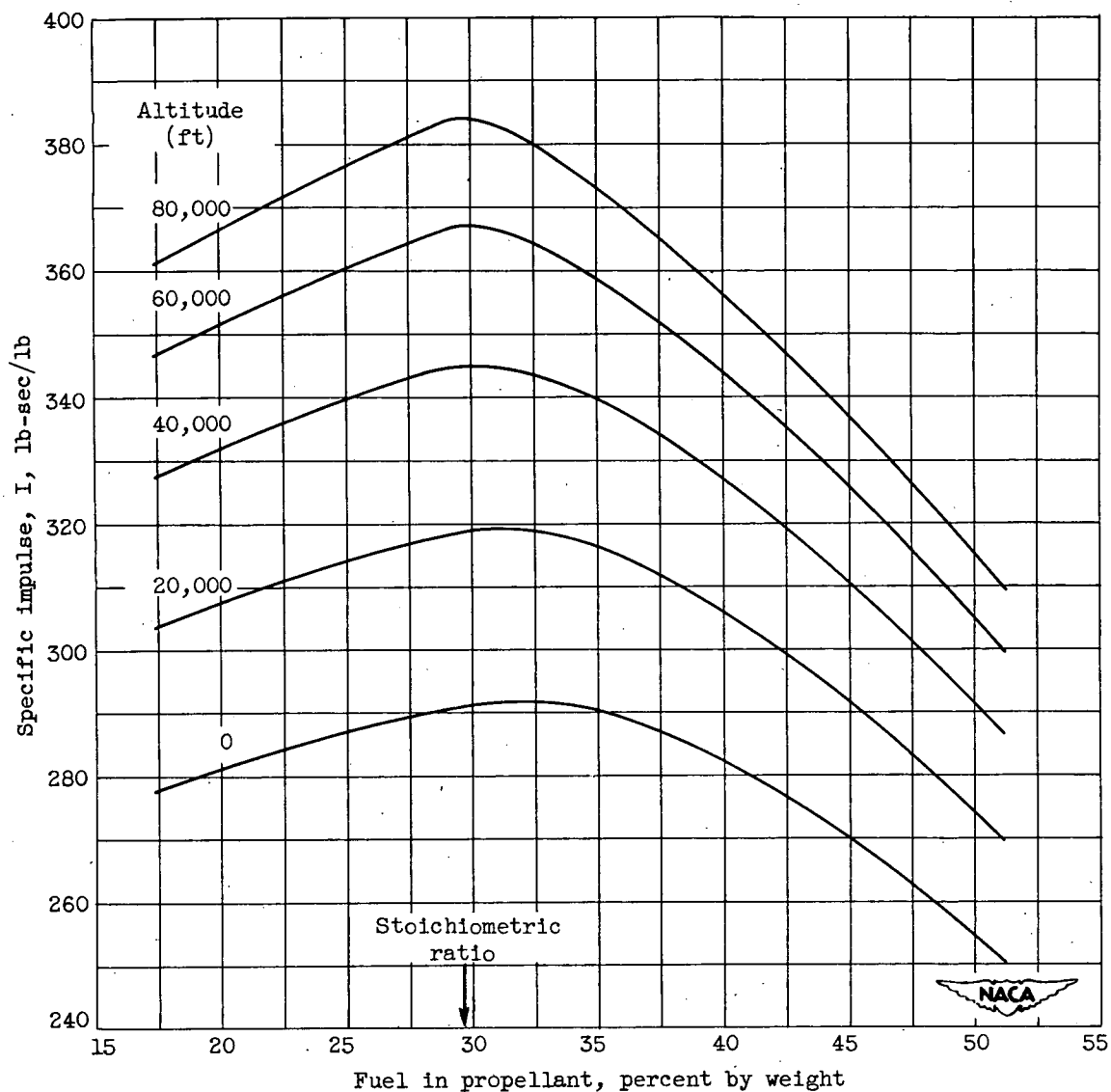


Figure 1. - Theoretical specific impulse of liquid ammonia with liquid oxygen bifluoride. Isentropic expansion assuming equilibrium composition; combustion-chamber pressure, 300 pounds per square inch absolute; exit pressure corresponding to altitude indicated.

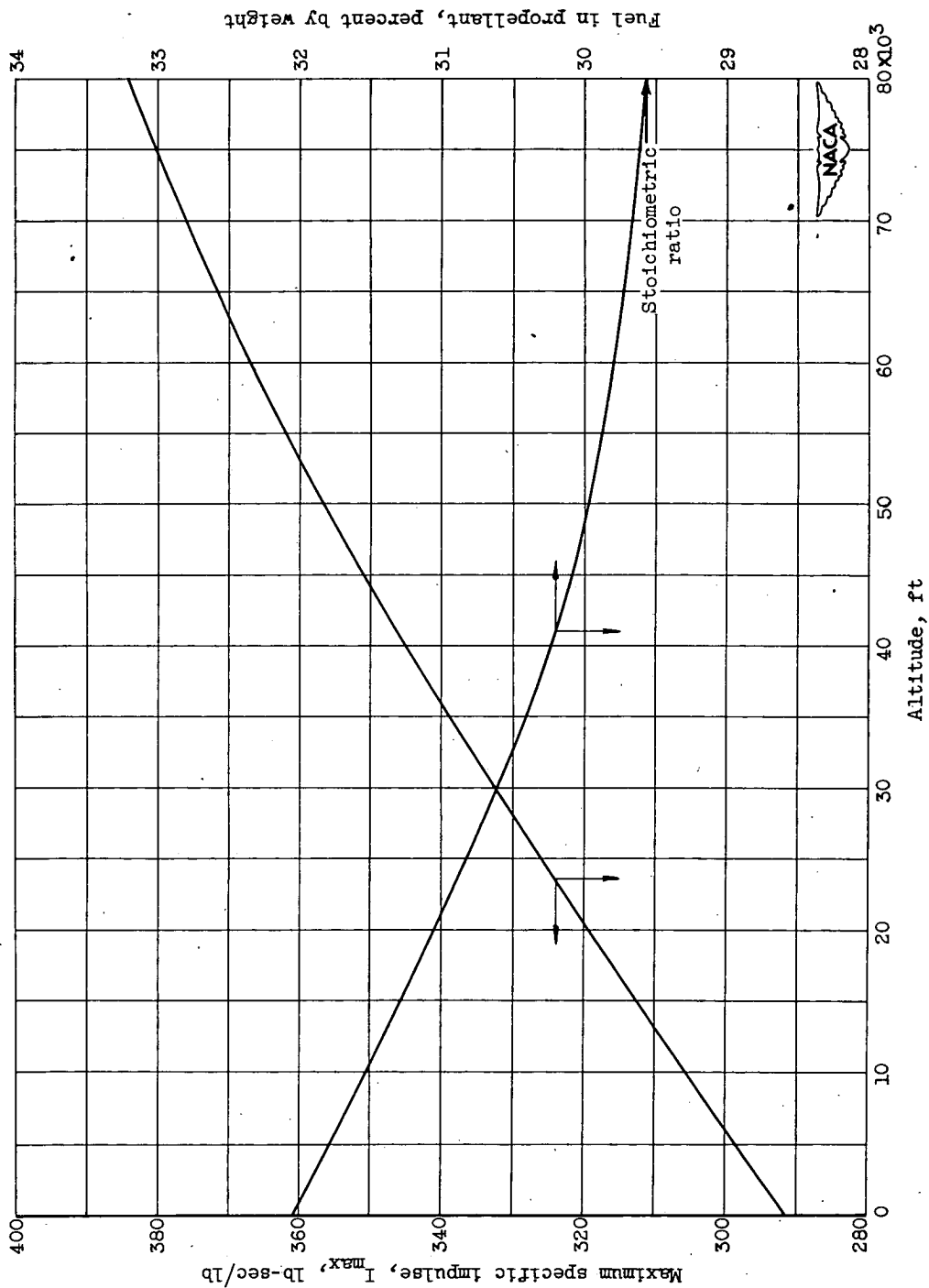


Figure 2. - Maximum theoretical specific impulse and corresponding weight percent of fuel in propellant of liquid ammonia with liquid oxygen bifluoride. Isentropic expansion assuming equilibrium composition; combustion-chamber pressure, 300 pounds per square inch absolute; exit pressure corresponding to altitude indicated.

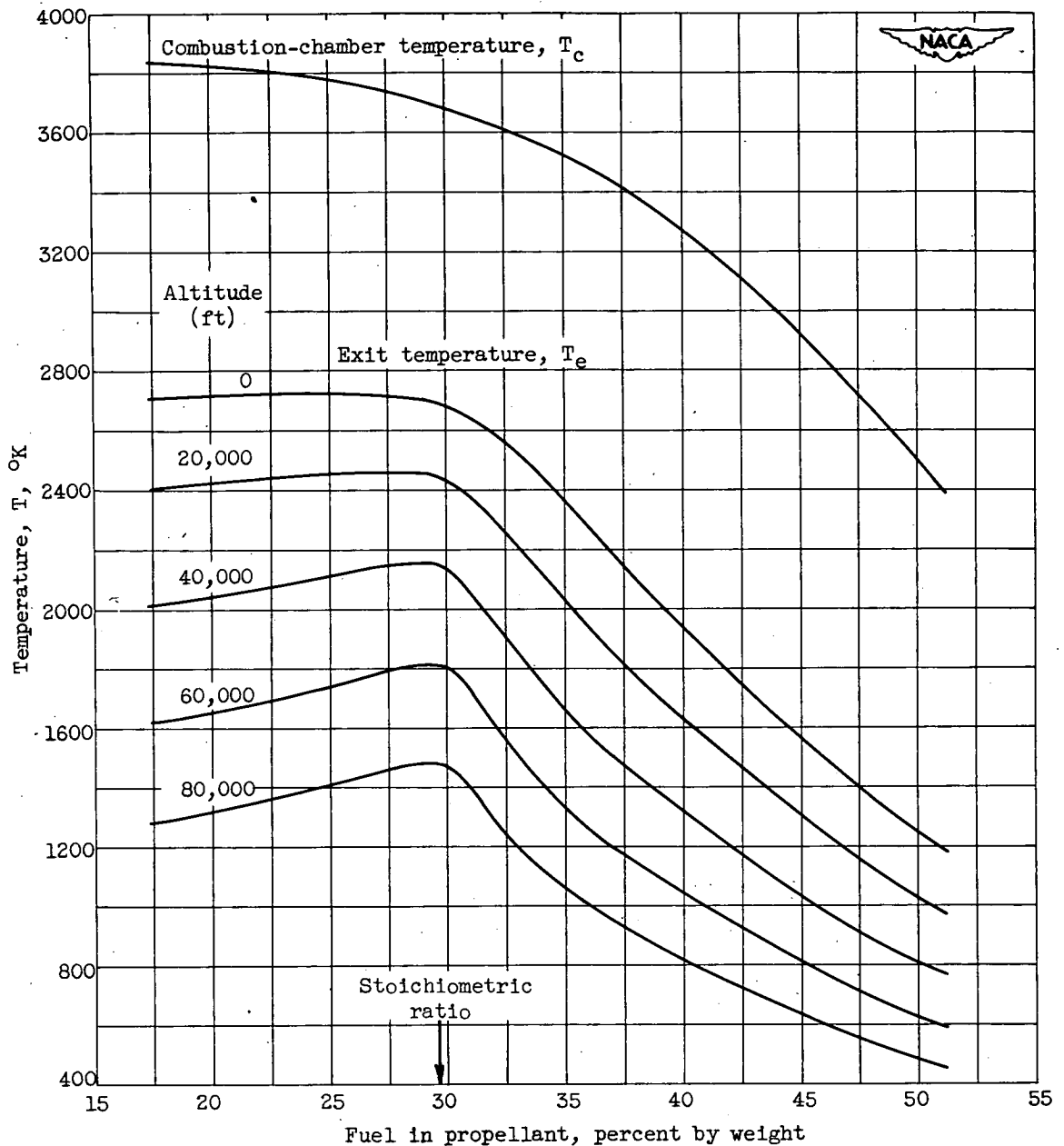


Figure 3. - Theoretical combustion-chamber temperature and nozzle-exit temperature of liquid ammonia with liquid oxygen bifluoride. Isentropic expansion assuming equilibrium composition; combustion-chamber pressure, 300 pounds per square inch absolute; exit pressure corresponding to altitude indicated.

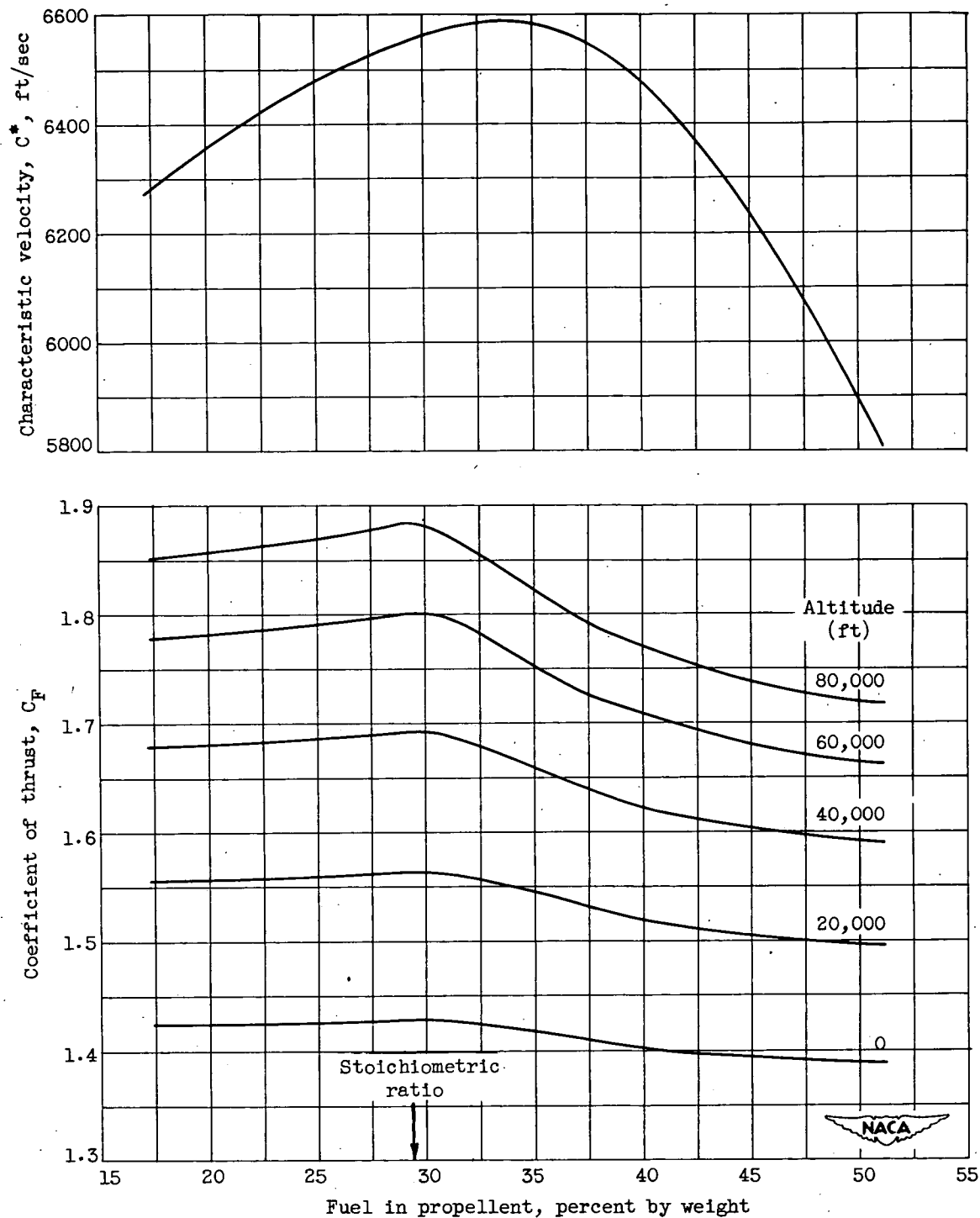


Figure 4. - Theoretical characteristic velocity and coefficient of thrust of liquid ammonia and liquid oxygen bifluoride. Isentropic expansion assuming equilibrium composition; combustion-chamber pressure, 300 pounds per square inch absolute; exit pressure corresponding to altitude indicated.

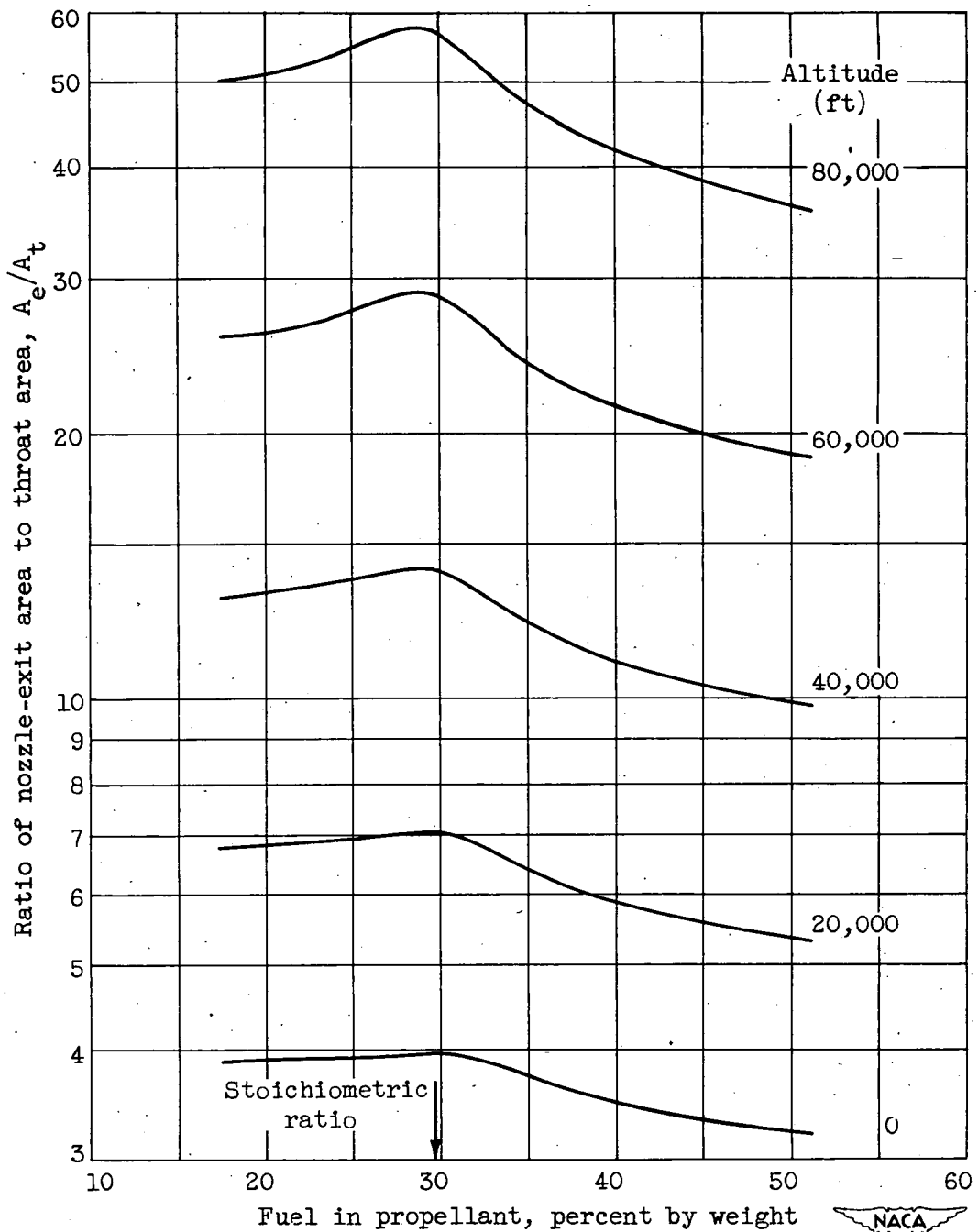


Figure 5. - Theoretical ratios of nozzle-exit area to throat area of liquid ammonia with liquid oxygen bifluoride. Isentropic expansion assuming equilibrium composition; combustion-chamber pressure, 300 pounds per square inch absolute; exit pressure corresponding to altitude indicated.

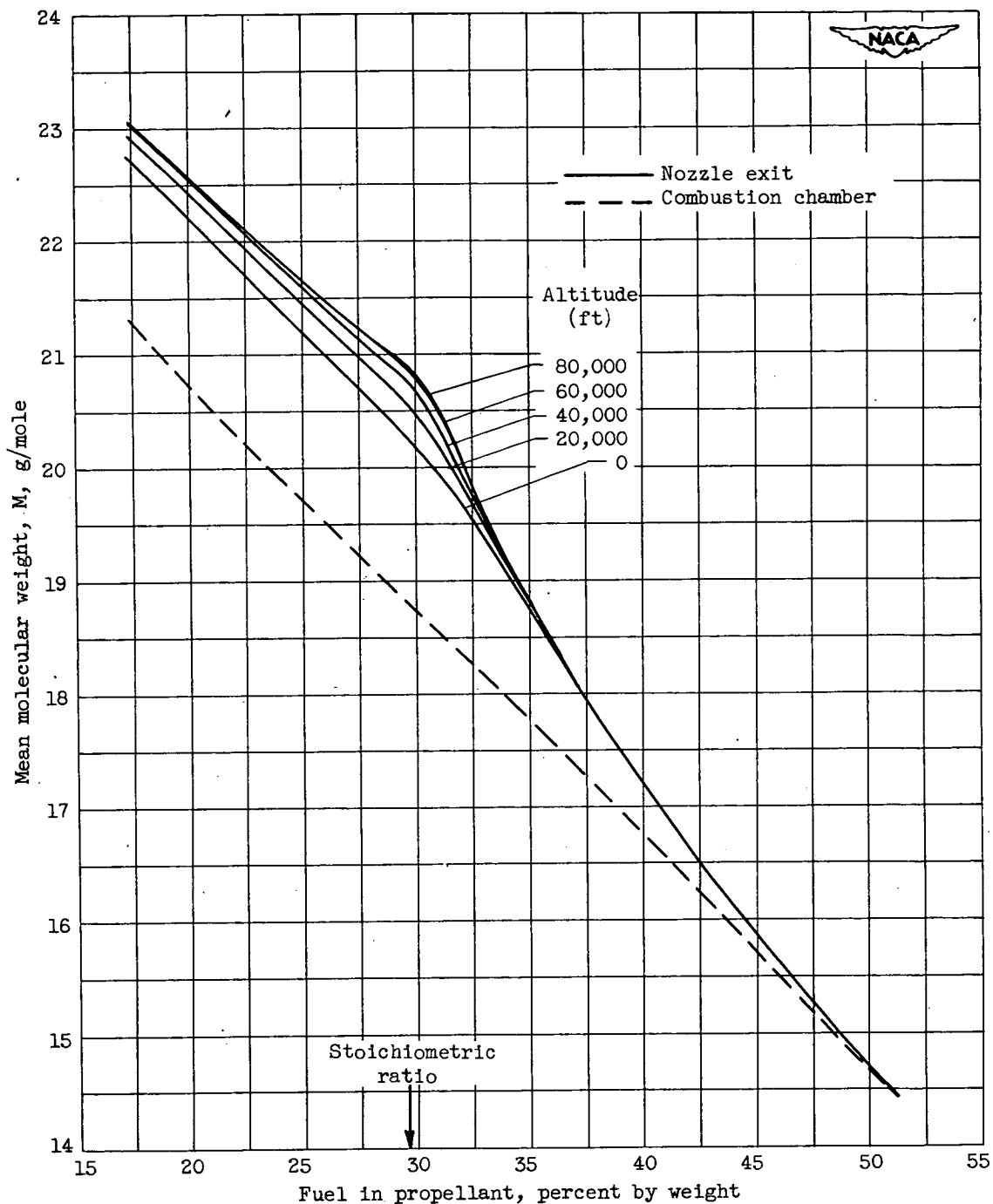


Figure 6. - Theoretical mean molecular weight in combustion chamber and at nozzle exit of liquid ammonia with liquid oxygen bifluoride. Isentropic expansion assuming equilibrium composition; combustion-chamber pressure, 300 pounds per square inch absolute; exit pressure corresponding to altitude indicated.

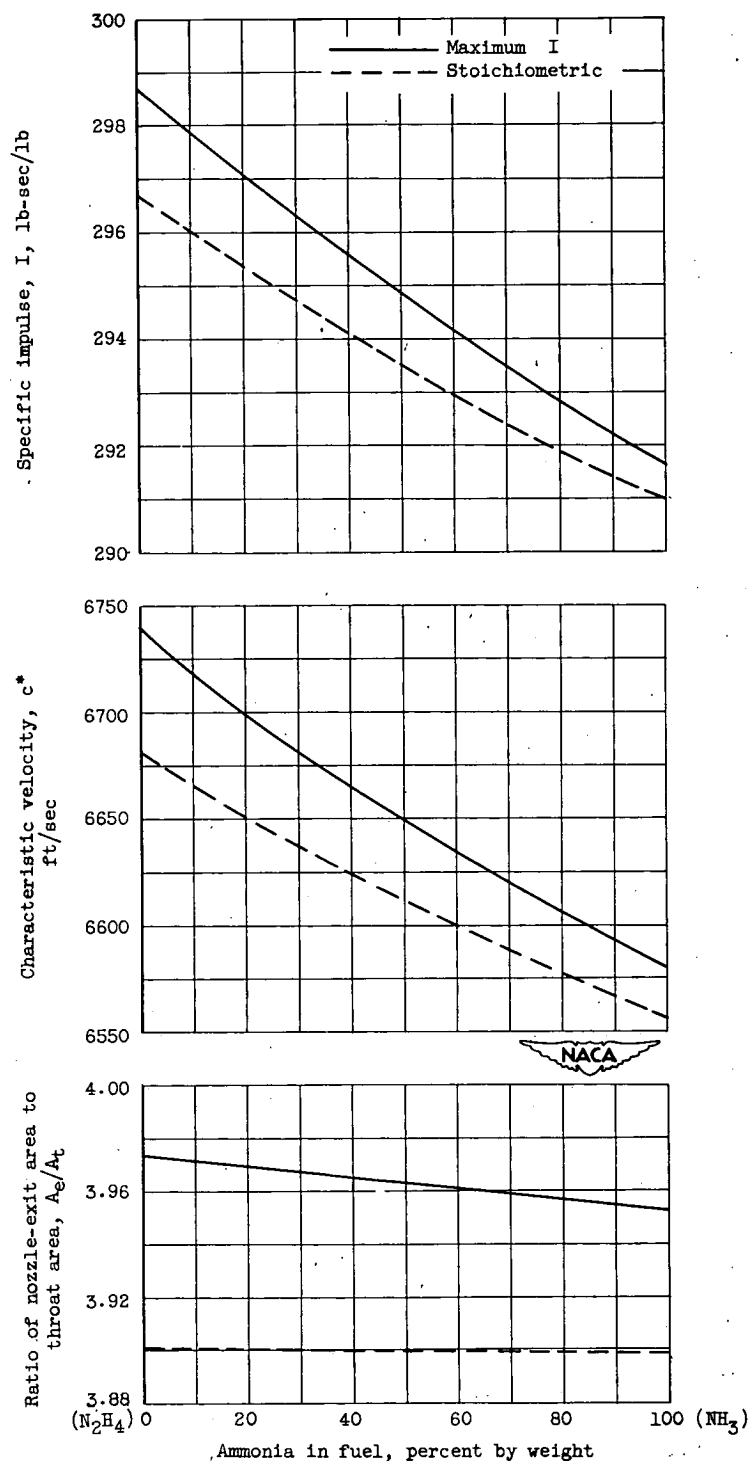


Figure 7. - Theoretical specific impulse, characteristic velocity, and ratio of nozzle-exit area to throat area for mixtures of ammonia and hydrazine with oxygen bifluoride. Isentropic expansion assuming equilibrium composition; combustion-chamber pressure, 300 pounds per square inch absolute; exit pressure, 1 atmosphere.